Design and Operational Performance of Double Crossover Intersection and Diverging Diamond Interchange

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Transportation planners and traffic engineers are facing the challenge of inventing ways to mitigate congestion during the peak hours. Alleviating delays and improving safety for passengers and pedestrians are the primary motives. One way of achieving these objectives is to search for alternative intersection and interchange designs. This paper presents the results of a study on two new alternate designs: double crossover intersection and diverging diamond interchange. These designs were studied for different traffic scenarios with the use of traffic simulation, and the results showed better performance during peak hours than that of similar corresponding conventional designs. Better performance includes better level of service, shorter delays, smaller queues, and higher throughput.

Transportation planners and traffic engineers are facing the challenge of mitigating congestion during the peak hours and at lower costs. Alleviating delays and improving safety for motor vehicles and pedestrians are primary motives. In urban areas, less land is available for constructing roads, and hence land should be used more judiciously by designing roads, intersections, and interchanges that occupy less right-of-way. One way of achieving all these objectives is to search for alternative intersection designs.

Researchers have developed several innovative intersection designs in the past to address these problems. These designs include the quadrant roadway intersection, median U-turn, superstreet median, jug handle, split intersection, and continuous flow intersection (CFI). The most influential factor in the intersection performance for heavy flows is achieved by reducing the number of phases in the signal cycle. The CFI especially is finding increasing acceptance in the United States lately (*1*).

Chlewicki (*2*) suggested two new designs for intersections and interchanges—the synchronized split-phasing (SSP) intersection and the diverging diamond interchange (DDI). As in the CFI, SSP design also disperses the flow of traffic before reaching the main intersection. The synchronized split-phasing design allows both the through and the left movements to cross over before the intersection (see Figure 1*a*).

The main goal of the DDI design is to better accommodate left-turn movements and hence eliminate a phase in the signal cycle. Figure 1*b*

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shows the layout of the diverging diamond interchange. The freeway portion does not change, but the movements off the ramps change for left turns. In a DDI, through and left-turn traffic on the crossroad maneuver differently from a conventional diamond interchange as the traffic crosses to the opposite side between the ramp terminals.

Chlewicki discusses the simulation tests performed for a case study intersection and interchange using Synchro as the simulation tool. Results showed that the SSP and DDI designs outperform similar corresponding conventional designs. In his conclusion, Chlewicki discusses the future scope of research including analysis of different volume ratios and turning movement ratios, and the speeds and superelevations to see how fast vehicles can travel practically in the crossover movements (*2*).

This paper analyzes further the designs presented by Chlewicki (*2*). Four traffic scenarios are considered, and pedestrian performance is simulated for one case. A comparison is done with conventional intersection and interchange designs. Additional analyses related to the capacities of these innovative designs are also performed and results reported.

In the first section, detailed designs of the intersection and interchange are presented. The second section presents the analysis methodology including the simulation tools used, signal setting criteria, performance measures, and the four scenarios modeled. The following sections discuss the results, conclusions, and recommendations.

DESCRIPTION OF DESIGNS

Double Crossover Intersection

In this paper, "double crossover intersection" (DXI) is used as a more descriptive name than synchronized split phasing. Figure 2 shows the layout of a DXI. The eastbound (EB) traffic (through and left turners) crosses over to the left side at signalized Intersection A, while the right-turners use the dedicated right lane before reaching A. The crossed traffic will cross over back to the right side at signalized Intersection C. The westbound (WB) traffic also crosses over in a similar way. At Intersection B, there is one through lane and one through+left-turn lane. No dedicated left-turn lanes are provided. Right-turn lanes are required for EB and WB traffic. Merging lanes for the northbound (NB) and southbound (SB) for right-turn movements are required. Radii of crossover movements can range from 150 to 200 ft, and the radius of the left-turn movement at B is 100 ft. Movements can be better understood by following the arrow markings in the figure. The NB and the SB traffic are exactly similar to the corresponding movements at a conventional intersection, with
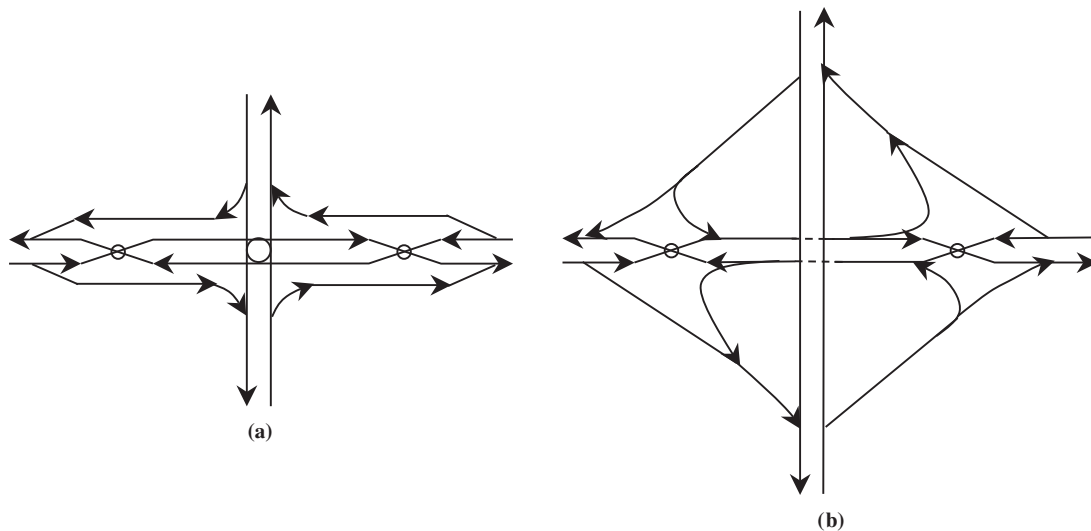
FIGURE 1   New designs for intersections and interchanges: (*a*) synchronized split-phasing intersection and (*b*) diverging diamond interchange (*2*).

one left-turn lane, one through lane, and one through+right-turn lane. No dedicated right-turn lanes are provided for NB and SB traffic; also, no merging lane for the EB and WB right-turn movements are necessary. The length of left-turn lane is 450 ft.

The conventional intersection that is compared with the DXI has the following design. There is only one signalized intersection in this case. For EB and WB traffic, there are two through lanes, one dedicated left-turn lane, and one dedicated right-turn lane. However, there is no merge lane for the right-turn movements from the NB and SB traffic. For NB and SB traffic, there are two through lanes and one dedicated left-turn lane, and there is no dedicated right-turn lane (right-turn movements share the lane with through movements). Also there is no merging lane for the right-turn movements from EB and WB traffic. The right-of-way requirement is the same as for the DXI design.

Diverging Diamond Interchange

Figure 3 shows the layout of a diverging diamond interchange (DDI). There are two on-ramps and two off-ramps that connect the crossroad and the freeway. The off-ramps have two left-turn lanes and one

right-turn lane. One left-turn lane and one right-turn lane lead to the on-ramp. The distance between the two terminals (and crossovers) is 500 ft. The arterial has one through lane, one through+left-turn lane, and one dedicated right-turn lane. The movements can be better understood by following the arrow markings in the figure. Two signalized intersections (A and B) are situated at the two crossover locations. The radii of the curves are same as the radii for DXI.

In rural high-speed environments, the nature of this directional crossing of through flows may be hazardous. A suggested forgiving design could provide curved approaches to motivate speed reduction by heightening drivers' awareness. In addition, the directional crossings are made more perpendicular and occupy shorter crossing distances (Figure 3*b*).

The conventional diamond interchange that is compared with the DDI has the following design (Figure 4). On-ramps and off-ramps are exactly the same as DDI, but there is a change in the number of lanes on the arterial. It has two through lanes, one dedicated left-turn lane, and one dedicated right-turn lane. Clearly, the section between the ramps needs more right-of-way as compared with the DDI (two extra left-turn lanes). There are two signals at A and B, and the distance between ramps is also 500 ft. The traffic movements can be better understood by viewing Figure 4.
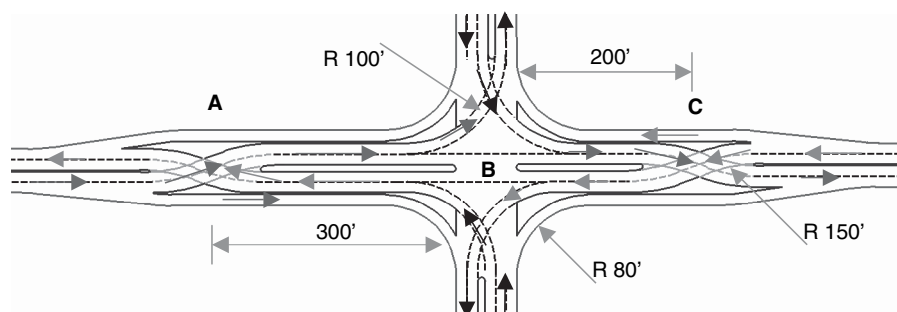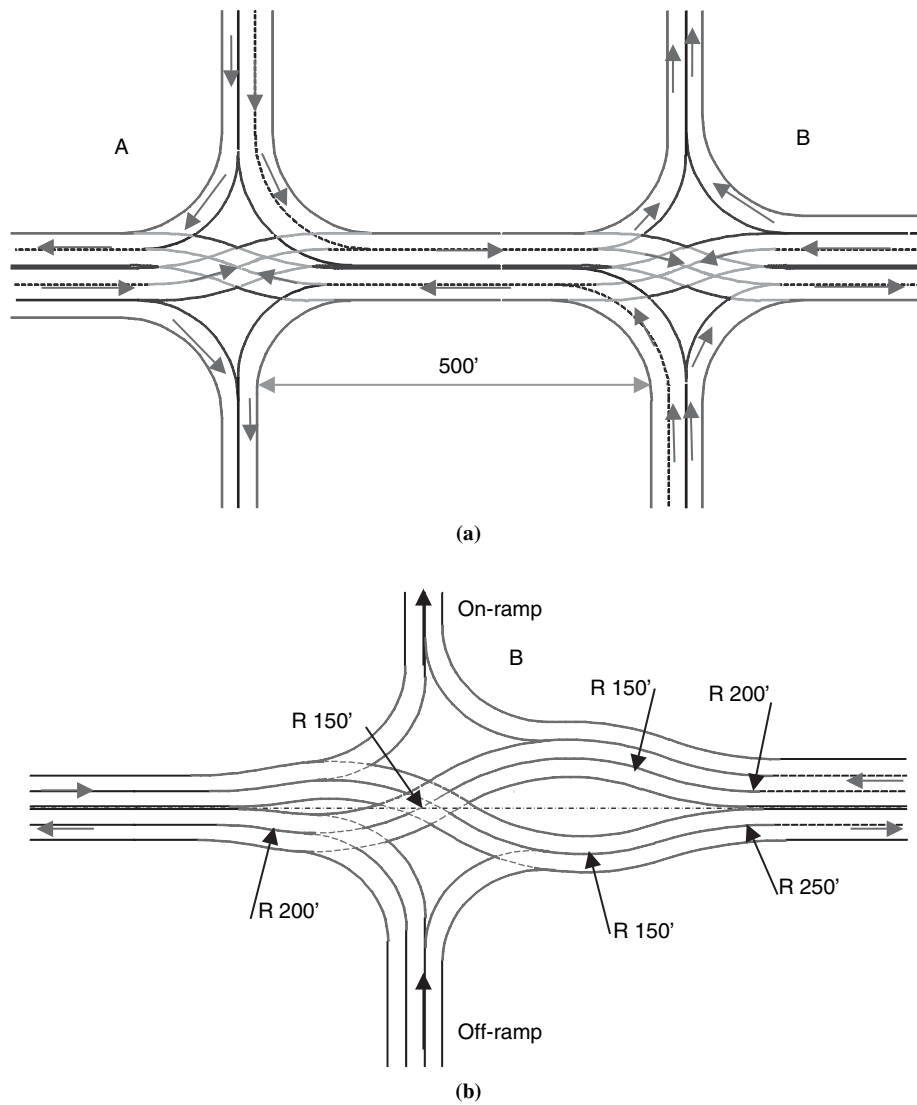

FIGURE 2   Double crossover intersection layout.

(a)

(b)

FIGURE 3   Diverging diamond interchange: (*a*) typical layout and (*b*) proposed geometric improvements at the right-side ramp terminal.
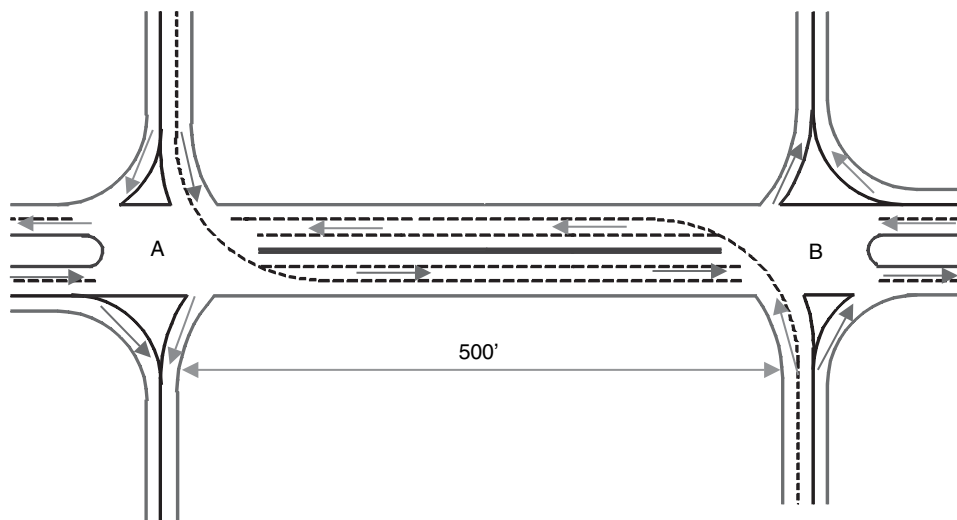

FIGURE 4   Conventional diamond interchange layout.

TABLE 1 DXI Versus Conventional Intersection—Traffic Scenarios (Without Pedestrians)

Traffic Scenario	Northbound (veh/hr)			Southbound (veh/hr)			Eastbound (veh/hr)			Westbound (veh/hr)			Total Flow (veh/hr)
	L	T	R	L	T	R	L	T	R	L	T	R	
Peak	348	792	96	400	1150	144	180	842	552	100	1024	124	5752
High	348	792	96	350	1100	100	150	800	500	100	950	124	5410
Medium	175	400	50	200	600	70	90	420	275	50	500	60	2890
Low	90	200	25	100	300	35	45	210	140	25	250	30	1450

NOTE: L = Left, T = Through, R = Right

ANALYSIS METHODOLOGY

Analysis of these innovative designs is done by using traffic simulation. Simulation software used for the analysis is VISSIM, a microscopic time step-based simulation model.

Analysis of DXI

The computer-assisted drafting (CAD) design shown in Figure 2 is transferred to VISSIM as background, and the links are drawn on top of it. Desired speeds, vehicle classes, and priority rules are defined, and signal heads are placed on the links. The DXI design is tested for four different traffic scenarios: peak volume, high volume, medium volume, and low volume. In urban conditions, it is reasonable to assume the desired speed for through movements to lie within 36 to 42 mph for cars and 30 to 36 mph for trucks. For the turn movements, it is assumed to lie within 15 to 18 mph for cars and 12 to 15 mph for trucks.

Traffic volumes in each direction are shown in Table 1. Signal phasing scheme is shown in Figure 5. Seven phases provide for all movements, three at the main intersection and two each at the two crossovers, although they basically operate within three phases. Northbound left turners (Phase 3) and SB left turners (Phase 2) go and store
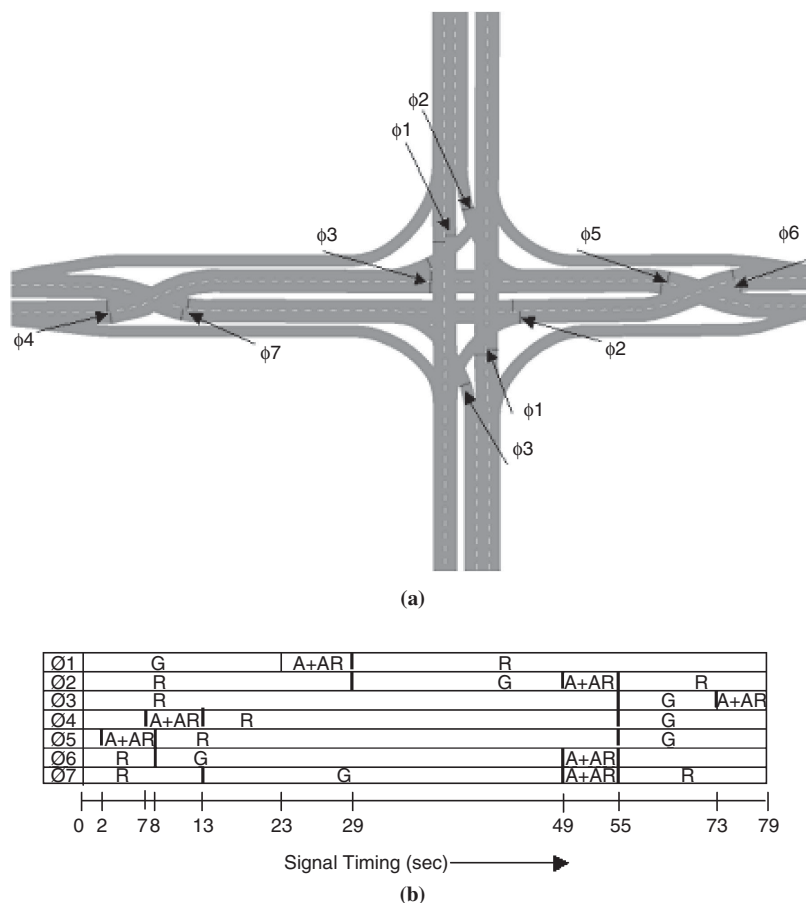

(a)

(b)

FIGURE 5 Signal setting for DXI (fixed time signal controller type) (G = green interval, A+AR = amber and all-red interval, R = red interval).

TABLE 2   Four-Lane DDI Versus Conventional Diamond Interchange—Traffic Scenarios

Traffic Scenario	Northbound Off-Ramp (veh/hr)			Southbound Off-Ramp (veh/hr)			Eastbound (veh/hr)			Westbound (veh/hr)			Total Flow (veh/hr)
	L	T	R	L	T	R	L	T	R	L	T	R	
High 3	750	0	450	750	0	450	450	850	550	450	850	550	6100
High 2	700	0	400	700	0	400	400	800	500	400	800	500	5600
High 1	650	0	350	650	0	350	350	750	450	350	750	450	5100
Medium	400	0	200	400	0	200	200	500	300	200	500	300	3200
Low	200	0	100	200	0	100	100	300	150	100	300	150	1700

NOTE: L = Left, T = Through, R = Right

in the link until the Phase 7 and Phase 5 turn green respectively. Cycle length of 79 s and signal timing shown in Figure 5 are the result of numerous trials. The amber time interval used is 3 s, and the all-red interval is 3 s at the end of every phase.

Performance criteria for the intersection design include average delay time per vehicle, average stop time per vehicle, average number of stops per vehicle, average queue length, and maximum queue length. After analyzing these four traffic scenarios, the capacity is estimated on the basis of two criteria: level of service (LOS) and model throughput. When the input volumes are so high that they result in LOS F (and beyond) for the intersection, or the model throughput is less than the input volume (assumed 100 vehicles per hour), then it can be concluded that the capacity is reached. The simulation period is 1 h, and the traffic arrivals are Poisson with exponentially distributed headways.

After determining the capacity for the DXI design, the next step is to compare the results obtained with the conventional intersection. A conventional four-legged intersection is analyzed in VISSIM for the same four scenarios and the same performance measures. The optimal signal setting for each traffic scenario is obtained from a signal optimization software, TRANSYT-7F.

Pedestrian movement is simulated in VISSIM. A pedestrian volume of 75 pedestrians per hour is assumed on each approach (EB, SB, WB, NB), and as there are three possible directions in which each of these volumes can be assigned, the directional volumes are equal to 25 pedestrians per hour (e.g., pedestrian trips generated at south approach are 75 pedestrians per hour, and the volume of trips toward east, west, and north is 25 pedestrians per hour each). The walking speed of pedestrians is assumed to be 4 ft/s. The LOS criterion for the pedestrians is average delay per pedestrian.

Analysis of DDI

Two designs of DDI are analyzed: four-lane DDI, in which the total number of lanes in the east–west direction is four, and six-lane DDI, in which the total number of lanes is six in the east–west direction. For the first case, five traffic flow scenarios are considered including one low flow, one medium flow, and three high flows. The performance of DDI is measured for high flows beyond the capacity of conventional diamond (Table 2). For the second case, six traffic flow scenarios are considered (Table 3). Finally, capacities of DDI are estimated for both designs.

The signal phasing scheme used for the DDI is shown in Figure 6. At the left-side ramp terminal in Phase 1, the EB through movements and the SB lefts are allowed to cross over, and in Phase 2, WB through movements are allowed to cross over. At the right-side ramp terminal in Phase 3, EB through movements are given green, and in Phase 4, the WB through movements and NB rights are given green. Phases 5 and 6 are for left-turn movements from the ramp onto the arterial. These left turners go and store in the link until Phase 2 and Phase 3 are given green respectively. In this way, efficient use can be made of the intersection design. Phase 5 and Phase 2 overlap, as there is no conflict between these two movements. In the same way, Phase 6 overlaps with Phase 3. The signal timing shown in Figure 6 is obtained as a result of several trials. For the given phasing sequence, the cycle length of 70 s is optimal for lower to medium flows, and a cycle length of 100 s gives best results for higher flows. The amber time used is 3 s, and the all-red period is 2 s at the end of every phase. Overall, the signal operates under two phases.

Capacity of the DDI design is estimated on the basis of the same two criteria mentioned for DXI. The results obtained for DDI are

TABLE 3   Six-Lane DDI—Traffic Scenarios

Traffic Scenario	Northbound Off-Ramp (veh/hr)			Southbound Off-Ramp (veh/hr)			Eastbound (veh/hr)			Westbound (veh/hr)			Total Flow (veh/hr)
	L	T	R	L	T	R	L	T	R	L	T	R	
V.High-3	1000	0	700	1000	0	700	700	1100	800	700	1100	800	8600
V.High-2	800	0	500	800	0	500	500	900	600	500	900	600	6600
V.High-1	700	0	400	700	0	400	400	800	500	400	800	500	5600
High	650	0	350	650	0	350	350	750	450	350	750	450	5100
Medium	400	0	200	400	0	200	200	500	300	200	500	300	3200
Low	200	0	100	200	0	100	100	300	150	100	300	150	1700

NOTE: L = Left, T = Through, R = Right
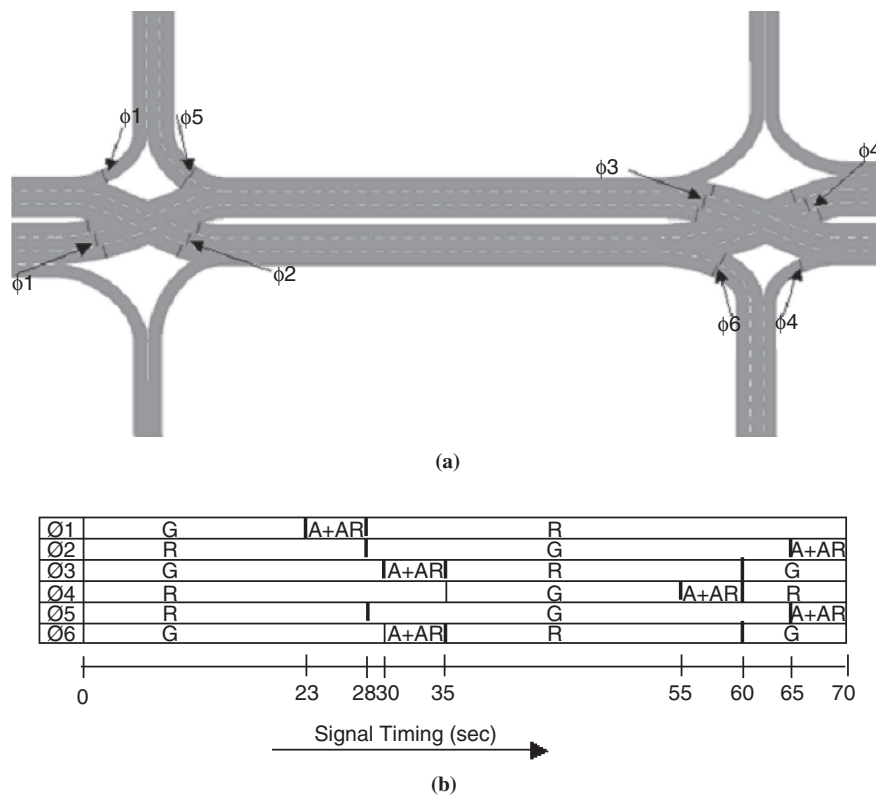
(a)

(b)

FIGURE 6   Signal setting for DDI (fixed time signal controller type) (G = green interval, A+AR = amber and all-red interval, R = red interval).

compared with the results of the conventional diamond interchange. The signal design and optimal signal setting for the conventional diamond interchange are obtained from PASSER-3 software.

RESULTS

The results of traffic simulation are shown in Tables 4–9. Table 4 shows the comparison of traffic performance of DXI with that of a conventional intersection. At lower and medium volumes, the performance is almost identical for both designs. However, for higher volumes ("peak" in Table 4), the performance of DXI is noticeably better than the conventional one. For the conventional design, the model throughput is about 1,000 vehicles per hour lower than the input flow, while for the DXI, the input flow and the model through-

put are similar (difference of about 100 vehicles per hour). The most important observation is that of the average delay per vehicle. For peak volumes, the delay per vehicle for conventional design is 219 s/veh, while the delay is 87 s/veh for the DXI. It is also noted that the number of stops, average stop time per vehicle, average queue, and maximum queue length are lower for the DXI when compared with the conventional design.

Traffic performance in the presence of pedestrians is studied for DXI, and the results are shown in Table 5. It can be seen that in spite of the inclusion of a pedestrian phase into the signal setting, the performance of DXI is still better than that of the conventional intersection at high volumes. In Table 5, the performance of pedestrians is shown for two types of crossings, adjacent crossing and diagonal crossing. Adjacent crossing is crossing a single approach, whereas diagonal crossing would be crossing two approaches at the inter-

TABLE 4   DXI Versus Conventional Intersection—Performance Results (Without Pedestrians)

Traffic Scenario	Input Flow (veh/hr)	Model Throughput (veh/hr)		Delay Time (s/veh)		Stop Time (s/veh)		No. of Stops		Ave Queue (ft)		Max Queue (ft)	
		DXI	Conv	DXI	Conv	DXI	Conv	DXI	Conv	DXI	Conv	DXI	Conv
Peak	5752	5630	4538	87	219	51	143	2.4	4.2	242.0	647.5	1057.1	1386.4
High	5410	5365	4540	45	174	29	105	1.2	3.4	63.0	490.0	392.2	1371.0
Medium	2890	2854	2856	26	36	19	29	0.8	0.7	17.2	46.4	166.6	238.2
Low	1450	1430	1434	25	23	19	18	0.8	0.6	8.1	14.0	81.1	100.7

NOTE: Conv = Conventional

TABLE 5   DXI—Performance Results (With Pedestrians)

Traffic Scenario	Flows (veh/hr) Input	Flows (veh/hr) Actual	Delay Time (s/veh)	Stop Time (s/veh)	No. of Stops	Max Queue (ft)
Peak	5752	5630	149	65	3.6	1673.7
High	5410	5365	86	43	2.3	1000
Medium	2890	2854	30	21	0.9	217.3
Low	1450	1430	27	19	0.8	100.2

Pedestrians	Delay Time (s/person)	Stop Time (s/person)	No. of Stops	Average Delay per Stop (s/person)
Diagonal crossing (e.g. S-W)	98	93	4	24
Adjacent crossing (e.g. S-N)	63	59	2	31

TABLE 6   Capacity of Conventional and DXI Designs

	E-W	W-E	E-S	W-N	S-W	S-N	N-E	N-S
Conventional (veh/hr)	600	450	100	100	170	575	175	575
DXI (veh/hr)	550	450	100	150	350	550	375	575

TABLE 8   Six-Lane DDI—Performance Results

Traffic Scenario	Input Flow (veh/hr)	Model Throughput (veh/hr)	Delay Time (s/veh)	Stop Time (s/veh)	No. of Stops (per veh)	Max Queue (ft)
V.High-3	8600	8200	58	28	1.1	785
V.High-2	6600	6500	32	19	0.8	450
V.High-1	5600	5500	28	18	0.7	421
High	5100	5040	27	18	0.7	305
Medium	3200	3170	18	11	0.6	186
Low	1700	1690	16	11	0.6	121

throughput, higher average delay per vehicle, higher stop time, and longer queues as compared with the DDI.

The maximum off-ramp flows for a DDI (700 vphpl) are greater than the corresponding flows in the conventional diamond (390 vphpl). When off-ramp flows are set to 390 vphpl, for a DDI, the capacity of the crossroad increased by 100 vphpl.

The results of six-lane DDI design are shown in Table 8. Apart from the three traffic scenarios discussed earlier, three very high-volume scenarios are analyzed. Capacities of each of the three designs are shown in Table 9. Capacities of the NB left turns, SB left turns, EB through, EB left, WB through, and WB left are shown. The DDI design does not have any exclusive left-turn lane, unlike the conventional diamond design, and the left turners share the lane with the through movements. Once again, the big difference between the results of DDI and the conventional diamond relates to the capacity of left-turn movements, the capacity of the DDI being twice that of the conventional diamond.

In this research, ramp terminal offsets of about 500 ft were assumed; however, the DDI design also works for shorter offsets. When the offset was reduced from 500 ft to 300 ft for the same signal setting (cycle length of 100 s), the capacity of NB and SB left turns (off-ramps) decreased by 200 vphpl for the six-lane design case. Capacity of all other movements remained unchanged. When choosing a shorter cycle length of 80 s, capacity of the off-ramp left turns decreased by only 100 vphpl, but the capacity of through traffic decreased by 75 vphpl approximately. In any case, the performance is still better than the corresponding conventional diamond design.

section (e.g., NE–SW). Apart from the standard performance measures such as average delay per person, average stop time per person, and so on, "average delay per person per stop"—which is the ratio of average delay per person and the average number of stops for that crossing—also is considered. This measure gives an indication of whether pedestrians are getting frustrated waiting for the signals and possibly disobeying the signals.

Capacities are estimated for both designs, for all signalized movements, and results are summarized in Table 6. Right-turn movements are not included as there are no right-turn signals; all of them are free right turns. From the results, the main contrasting difference between the capacities of these designs is for left turns (S–W and N–E). Capacity of the left turns in a DXI design is more than twice that of the conventional design. This finding suggests that DXI is very suitable at places where there are heavy left-turn movements.

The results for a four-lane DDI are shown in Table 7. Performances for lower and medium volumes are nearly identical in both designs (DDI and the conventional diamond). However, results from higher volumes show that this conventional diamond has lower model

CONCLUSIONS

Two novel intersection and interchange designs were analyzed and compared with conventional designs. The following conclusions can be made from the analysis and results.

TABLE 7   Four-Lane DDI Versus Conventional Diamond Interchange—Performance Results

Traffic Scenario	Input Flow (veh/hr)	Model Throughput (veh/hr) DDI	Model Throughput (veh/hr) Conv	Delay Time (s/veh) DDI	Delay Time (s/veh) Conv	Stop Time (s/veh) DDI	Stop Time (s/veh) Conv	No. of Stops DDI	No. of Stops Conv	Max Queue (ft) DDI	Max Queue (ft) Conv
High 3	6100	5800	5228	62	105	32	55	1.4	2.4	1191	1665
High 2	5600	5380	5187	40	91	24	46	0.9	2.3	1000	1170
High 1	5100	4912	4869	32	66	20	35	0.8	1.8	482	1108
Medium	3200	3074	3104	20	26	12	13	0.7	0.9	239	262
Low	1700	1631	1631	17	20	11	11	0.6	0.8	123	120

NOTE: Conv = Conventional

TABLE 9   Capacity of Conventional and DDI Designs

Design	Northbound Off-Ramp (veh/hr/ln)	Southbound Off-Ramp (veh/hr/ln)	Eastbound (veh/hr/ln)		Westbound (veh/hr/ln)	
	L	L	L	T	L	T
Diverging diamond (4 lanes)	600	600	600(L/T)	600	600(L/T)	600
Diverging diamond (6 lanes)	700	700	600(L/T)	600	600(L/T)	600
Conventional diamond	390	390	330	600	330	600

NOTE: L = Left, T = Through

Double Crossover Intersection

• For higher traffic volumes, the DXI has better performance and offers lower delays (less than 60%), fewer stops, lower stop time, and shorter queue lengths as compared with the performance of the conventional design. For lower volumes, the performance of the DXI and conventional intersection are similar.

• Capacity of the through movements is the same for both designs. However, the capacity of left-turn movements (northbound and southbound) for the DXI is twice that of the conventional design. This suggests that the DXI may be suitable to situations in which there are heavy left-turn movements in two opposing directions.

• Pedestrian performance is measured by average delay per person per stop. The DXI offers a LOS C with this measure. However, the number of stops for crossing is likely higher than corresponding number of stops at a conventional intersection.

• This design has two additional signals where through vehicles crisscross, making the intersection more complex and safety questionable.

Diverging Diamond Interchange

• For higher traffic volumes, the DDI has better performance and offers lower delays, fewer stops, lower stop time, and shorter queue lengths as compared with the performance of the conventional design. For lower volumes, the performance of the DDI and conventional intersection are similar.

• Capacity for all signalized movements is higher for the DDI as compared with the conventional diamond. Especially, capacity of the left-turn movements is twice that of the corresponding left-turn capacity of the conventional diamond. The DDI design is very superior to the conventional diamond because exclusive left-turn lanes are not necessary.

• Conventional diamond design that is comparable with the four-lane DDI consists of six lanes on the bridge section (two through and one left turn in each direction, east–west and west–east). When higher capacity is needed, it would be a good application to convert to a six-lane DDI instead of pursuing the costly option of widening bridges and approaches with dual left lanes in each direction.

• While the DDI does not allow through movements from off- to on-ramps, it allows U-turn movements with fewer conflicts than at a conventional diamond interchange.

FUTURE RESEARCH

The safety aspects of the suggested designs need to be studied in more detail. A surrogate safety assessment model is currently under development at FHWA, and after its completion, we expect to use it to compare the safety aspects of DDI, DXI, and conventional diamond. The proposed safety model aims at extracting the safety features from traffic simulation models (VISSIM, AIMSUN, and TEXAS Model) by analyzing the trajectory of vehicles and estimating their proximity. Another recommendation would be to compare the proposed DDI performance with the performance of a single-point diamond interchange. Finally, pedestrian movements on a DDI also need to be studied.

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